Production mechanism of fully heavy tetraquarks in proton-proton collisions

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Contents

Introduction

- Standard mesons are of the $q\bar{q}$ type (Zweig-Gell-Mann)
- Quarkonia are of the $Q\bar{Q}$ type.
- Jaffe proposed existence of $q\bar{q}q\bar{q}$ (tetraquarks) and discussed it in the context of MIT bag model.
- Some people considered $X(3870)$ discovered by the Belle collaboration as $q\bar{q}c\bar{c}$ tetraquark.
- Fully heavy tetraquarks were discussed in the literature in different theoretical approaches.
- LHCb announced a new state $T_{4c}(6900)$ which decays into $J/\psi J/\psi$ channel.
- Hypothesis: we observe a quantal state of $c\bar{c}c\bar{c}$ system.

Introduction

- Ground state $c\bar{c}c\bar{c}$ is at $M \sim 5.8$ GeV, decays e.g. $T_{4c} \to \mu^+\mu^-\mu^+\mu^-$.
- The observed state is most probably excited state of the $c\bar{c}c\bar{c}$ system. Spin and parity remain unknown.
- Different models predict different J^{PC} assignments. Most often 0^+, 1^+, 2^+, sometimes 0^-.
- The decay branching fraction into $J/\psi J/\psi$ is most probably of the order of 50 % (large), but is strictly unknown.
- New Era has just opened and the topic will be studied at the LHC run 2 and HL-LHC.
  Could be also studied at the FCC.
  I shall argue that FCC may be much better.

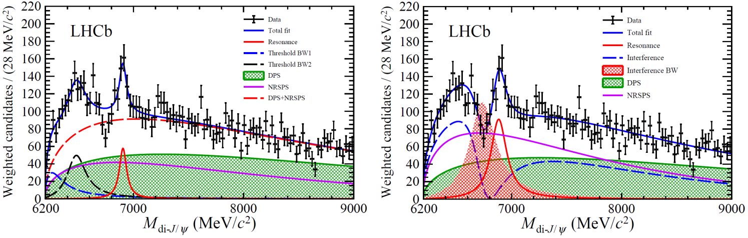
Introduction

- Theoretical studies concentrated (almost totally) on spectroscopy.
- The tetraquark is then diquark-antidiquark system $(cc)(\bar{c}\bar{c})$.
  But could be also genuine $c\bar{c}c\bar{c}$ system (such calculations are much more difficult).
- The decays were studied mostly for the ground state fully heavy tetraquarks.
- The mechanism of the reaction was almost not studied.

Introduction

- Our recent work concentrated on the mechanism of tetraquark production.
- I will try to address the issue why the fully heavy tetraquarks were not observed before LHC and could be produced at the LHC and even more efficiently at the FCC.
- This presentation will be partially based on:
  R. Maciula, W. Schäfer and A. Szczurek,
  "On the mechanism of $T_{4c}(6900)$ tetraquark production",
  Phys. Lett. **B812** (2021) 136010.

LHCb result



Combined result from $\sqrt{s} = 7, 8, 13$ TeV.
No cross section given by the LHCb collaboration.

The spectrum could be explained by a fit within coupled-channel approach, e.g. (Dong, Baru, Guo, Hanhart, Nefediev, Phys.Rev.Lett.126, 132001 (2021)).
But physics depends on many more (y, p_t) kinematical variables.

General idea

After many years of investigation there is no agreement on production mechanism even for quarkonia, pure $Q\bar{Q}$ states. For $C = +1$ quarkonia rather color singlet mechanism dominates. How big is color octet contribution is not quite clear at present.

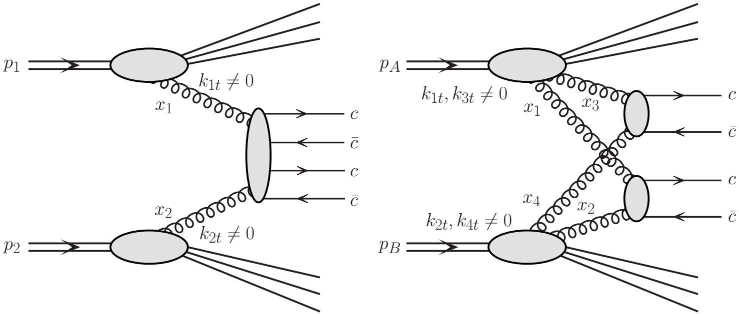
The production mechanism of the $c\bar{c}c\bar{c}$ must be much more complicated. One has to produce four (heavy) (anti)quarks in a narrow window of mass and close to each other in ordinary space.

The reaction mechanism for $C = +1$ tetraquark production (the LHCb case) can be categorized as:

(a) $c\bar{c}c\bar{c}$ are produced in color singlet state,

(b) $c\bar{c}c\bar{c}$ are produced in color octet state and extra emission(s) of soft gluon(s) is(are) necessary to bring the $c\bar{c}c\bar{c}$ system to color singlet state relevant for the tetraquark hadron.

Mechanisms of $c\bar{c}c\bar{c}$ production



Rysunek: Two dominant reaction mechanisms of production of $c\bar{c}c\bar{c}$ nonresonant continuum. The left diagram represents the SPS mechanism and the left diagram the DPS mechanism.

Luszczak, Maciula, Hameren, Schäfer, Szczurek

A sketch of the formalism, $c\bar{c}c\bar{c}$ SPS

In the present study both the SPS and the DPS contributions are calculated in the framework of k_T-factorization. According to this approach the SPS cross section for $pp \to c\bar{c}c\bar{c}\,X$ reaction can be written as

$$d\sigma_{pp \to c\bar{c}c\bar{c}\;X} = \int dx_1 \frac{d^2 k_{1t}}{\pi} dx_2 \frac{d^2 k_{2t}}{\pi} \mathcal{F}_g(x_1, k_{1t}^2, \mu^2) \mathcal{F}_g(x_2, k_{2t}^2, \mu^2) \, d\hat{\sigma}_{g^* g^* \to c\bar{c}c\bar{c}} \; . \quad (1)$$

$\mathcal{F}_g(x, k_t^2, \mu^2)$ is the unintegrated or transverse momentum dependent gluon distribution function (gluon uPDF).

The uPDF depends on:

(a) longitudinal momentum fraction x,

(b) transverse momentum squared k_t^2 of the partons entering the hard process,

(c) (factorization) scale of the hard process μ^2.

A sketch of the formalism, $c\bar{c}c\bar{c}$ SPS

The elementary cross section can be written as:

$$d\hat{\sigma}_{g^* g^* \to c\bar{c}c\bar{c}} = \frac{1}{(2!)^2} \prod_{l=1}^{4} \frac{d^3\vec{p}_l}{(2\pi)^3 2E_l} (2\pi)^4 \delta^4 (\sum_{l=1}^{4} p_l - k_1 - k_2) \frac{1}{\mathrm{flux}} \overline{|\mathcal{M}_{g^* g^* \to c\bar{c}c\bar{c}}(k_1, k_2, \{p_l\})|^2} , \tag{2}$$

where E_l and p_l are energies and momenta of final state charm quarks.
The matrix element takes into account that both gluons entering the hard process are off-shell with the virtualities:
$k_1^2 = -k_{1t}^2$ and $k_2^2 = -k_{2t}^2$.
In numerical calculations we limit ourselves to the dominant gluon-gluon fusion channel of the $2 \to 4$ type parton-level mechanism.
We checked numerically that the $q\bar{q}$-annihilation can be safely neglected in the kinematical region under consideration.

A sketch of the formalism, $c\bar{c}c\bar{c}$ DPS

Within the factorized ansatz, the dPDFs are taken as:

$$D_{1,2}(x_1, x_2, \mu) = f_1(x_1, \mu)\, f_2(x_2, \mu)\, \theta(1 - x_1 - x_2)\,, \qquad (3)$$

where $D_{1,2}(x_1, x_2, \mu)$ is the dPDF and $f_i(x_i, \mu)$ are the standard single PDFs for the two partons in the same proton.

The factor $\theta(1 - x_1 - x_2)$ ensures that the sum of the two parton momenta does not exceed 1.

The differential cross section for $pp \to c\bar{c}c\bar{c}\ X$ reaction within the DPS mechanism can be expressed as follows:

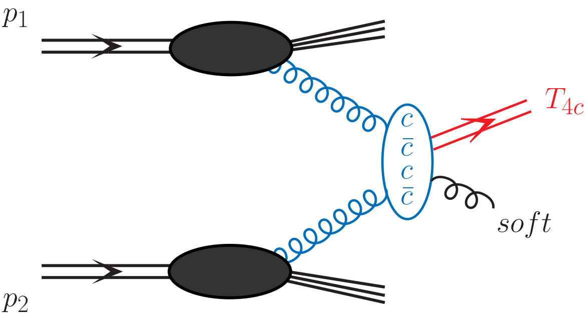
$$\frac{d\sigma^{DPS}(pp \to c\bar{c}c\bar{c}\ X)}{d\xi_1 d\xi_2} = \frac{m}{\sigma_{\mathrm{eff}}} \cdot \frac{d\sigma^{SPS}(pp \to c\bar{c}\ X)}{d\xi_1} \cdot \frac{d\sigma^{SPS}(pp \to c\bar{c}\ X)}{d\xi_2}, \qquad (4)$$

where ξ_1 and ξ_2 stand for generic phase space kinematical variables for the first and second scattering, respectively.

The combinatorial factor m is equal 0.5 for the $c\bar{c}c\bar{c}$ case.

Here, $d\sigma^{SPS}(pp \to c\bar{c}\ X)$ is cross sections for the off-shell initial state partons.

A sketch of the formalism for T_{4c} production



Rysunek: Mechanisms of T_{4c} production in our coalescence model.

soft gluon emission for initial color octet
as in color evaporation model.

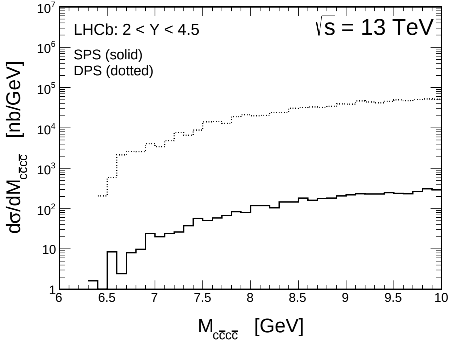
A sketch of the formalism for T_{4c} production

The $c\bar{c}c\bar{c} \to T_{4c}(6900)$ transition can be written as follows:

$$\frac{d\sigma_{T_{4c}}}{d^3\vec{P}_{T_{4c}}} = F_{T_{4c}} \int_{M_{T_{4c}}-\Delta M}^{M_{T_{4c}}+\Delta M} d^3\vec{P}_{4c}\, dM_{4c} \frac{d\sigma_{c\bar{c}c\bar{c}}}{dM_{4c} d^3\vec{P}_{4c}} \delta^3(\vec{P}_{T_{4c}} - \frac{M_{T_{4c}}}{M_{4c}}\vec{P}_{4c}),$$

where $F_{T_{4c}}$ is the probability of the $c\bar{c}c\bar{c} \to T_{4c}$ transition which is unknown and could be fitted to a future experimental data, $M_{T_{4c}} = 6.9$ GeV is the mass of T_{4c} tetraquark and M_{4c} is the invariant mass of the $c\bar{c}c\bar{c}$-system. In the numerical calculations we take $\Delta M = 100$ MeV.

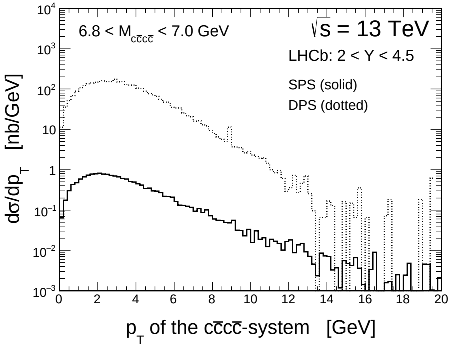
Results



Rysunek: Distribution of invariant mass of four $c - \bar{c}$ system. Here $\sqrt{s} = 13$ TeV and each quark/antiquark rapidity is contained in the rapidity interval (2,4.5). The solid line is for SPS and the dashed line for DPS contributions.

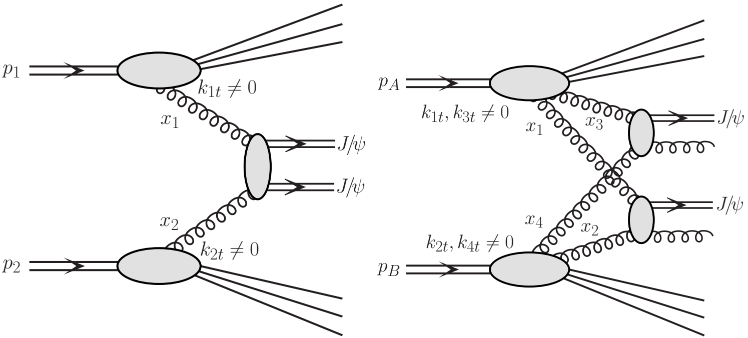
The maximum of the cross section is reached above 6.9 GeV.

Results



Rysunek: Distribution of $p_{t,4c}$ of four quark-antiquark system within invariant mass window $(M_R - 0.1\text{GeV}, \mathrm{M_R} + 0.1\text{GeV})$. Here $\sqrt{s} = 13$ TeV and each $c/\bar{c}$ rapidity is contained in the rapidity interval (2,4.5). The solid line is for SPS and the dashed line for DPS contributions.

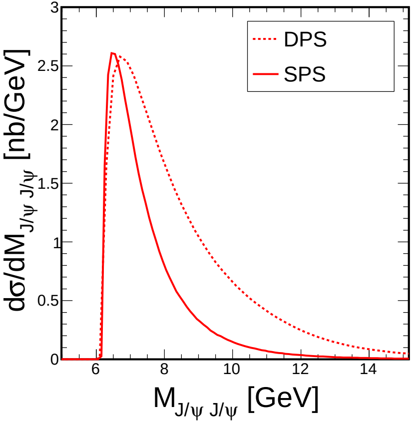
$pp \to J/\psi J/\psi$ background



Rysunek: Two dominant reaction mechanisms of production of $J/\psi J/\psi$ nonresonant continuum. The left diagram represent the SPS mechanism (box type) and the right diagram the DPS mechanism.

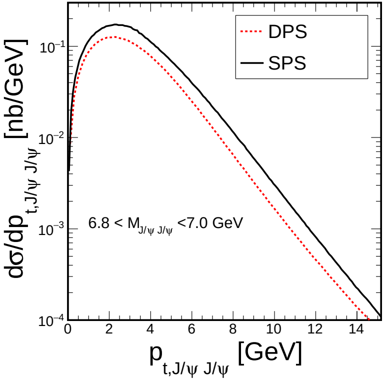
We studied such a channel in the past.
At the LHCb kinematics both contributions are similar.

$J/\psi J/\psi$ background



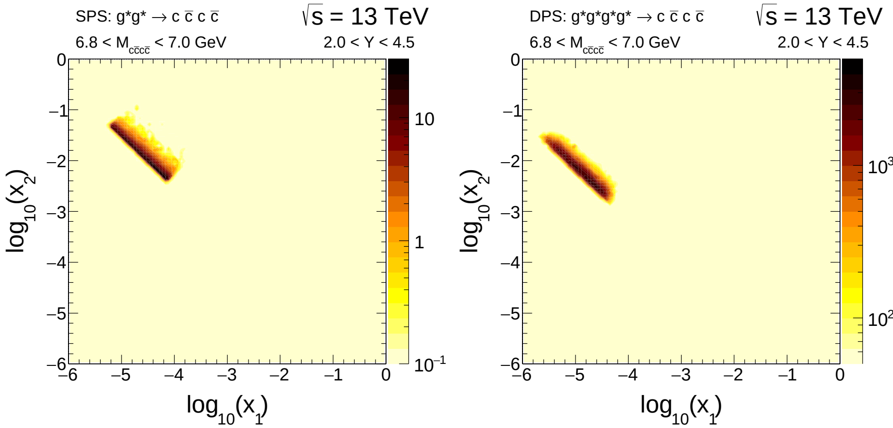
Rysunek: Distribution in invariant mass of the $J/\psi J/\psi$ system for SPS (solid line) and DPS (dashed line). In this calculation $\sqrt{s} =$ 13 TeV and we assumed that both J/ψ mesons have rapidity in the (2,4.5) interval.

Background in the tetraquark mass window



Rysunek: Distribution in transverse momentum of the J/ψ pairs within the invariant mass window $(M_R - 0.1\mathrm{GeV}, \mathrm{M_R} + 0.1\mathrm{GeV})$ for SPS (solid line) and DPS (dashed line) contributions. Here $\sqrt{s} = 13$ TeV. The red lines represent the signal from the naive coalescence approach multiplied by different prefactor for the SPS (solid line) and DPS (dashed line) $c\bar{c}c\bar{c}$ contributions.

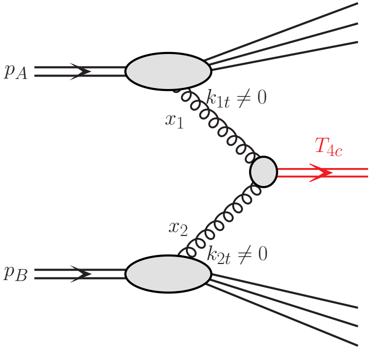
Longitudinal momentum fractions



Rysunek: For SPS (left) and DPS (right).

rather small x enter the calculation

$g^* g^* \longrightarrow T_{4c}(6900)$ resonance production, examples of the spin-parity assignment



Rysunek: The mechanism of gluon-gluon fusion leading to the production of the $T_{4c}(6900)$ tetraquark.

We studied $g^* g^* \longrightarrow Q\bar{Q}$ for pseudoscalar and scalar quarkonia (Babiarz, Pasechnik, Schäfer, Szczurek)

$g^*g^* \to T_{4c}(6900)$ mechanism

The off-shell gluon fusion cross sections is proportional to a form-factor, which depends on the virtualities of gluons, $Q_i^2 = -k_i^2$:

$$d\sigma_{g^*g^*\to 0^-} \propto \frac{1}{k_{1t}^2 k_{2t}^2} (\vec{k}_{1t} \times \vec{k}_{2t})^2 \, F^2(Q_1^2, Q_2^2)$$

$$d\sigma_{g^*g^*\to 0^+} \propto \frac{1}{k_{1t}^2 k_{2t}^2} \Big((\vec{k}_{1t} \cdot \vec{k}_{2t})(M^2 + Q_1^2 + Q_2^2) + 2Q_1^2 Q_2^2 \Big)^2 \, \frac{F^2(Q_1^2, Q_2^2)}{4X^2} \, , (6)$$

with $X = (M^4 + 2(Q_1^2 + Q_2^2)M^2 + (Q_1^2 - Q_2^2)^2)/4$.
Note, that for the 0^+ assignment we use only the TT coupling, as in analogy with Babiarz et al. we expect the LL contribution to be smaller.
In our calculation for the tetraquark production we also use the KMR UGDFs.

$g^* g^* \to T_{4c}(6900)$ mechanism

The $g_{ggT_{4c}}$ coupling constants are in both cases roughly adjusted to get the signal-to-background ratio of the order of 1.

In our calculation here we use the nonfactorizable monopole form factor:

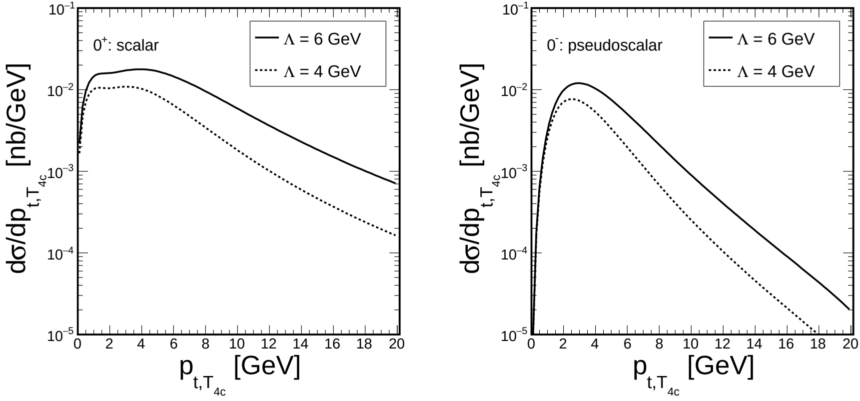
$$F(Q_1^2, Q_2^2) = \frac{\Lambda^2}{\Lambda^2 + Q_1^2 + Q_2^2} \, , \tag{7}$$

where Q_1^2 and Q_2^2 are gluon virtualities.

Λ is a free parameter.

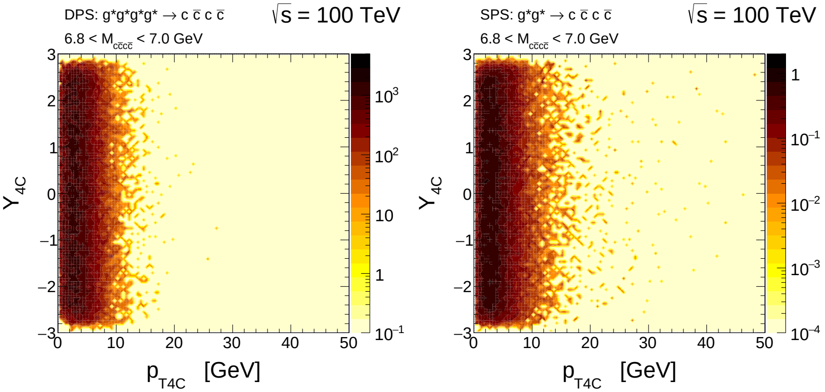
In future such a form factor should be calculated.

$g^*g^* \to T_{4c}(6900)$ mechanism



Rysunek: Transverse momentum distribution of the $T_{4c}(6900)$ tetraquark for the 0^+ (left panel) and 0^- (right panel) assignments. Here $\sqrt{s} = 13$ TeV. We show results for the KMR UGDF and $\Lambda = 6$ GeV (solid line) and $\Lambda = 4$ GeV (dashed line).

Results for FCC with the tetraquark mass window

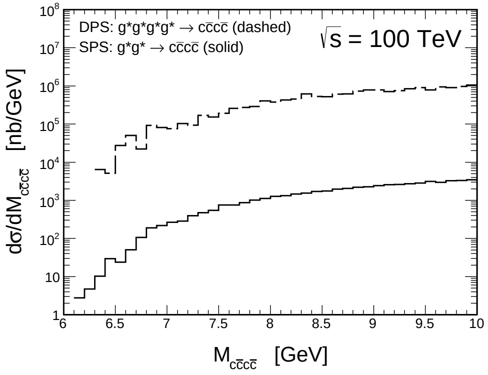


Rysunek: Two-dimensional distribution in the tetraquark mass window.

Quite regular behaviour

For illustration we shall fix the rapidity interval as for ATLAS

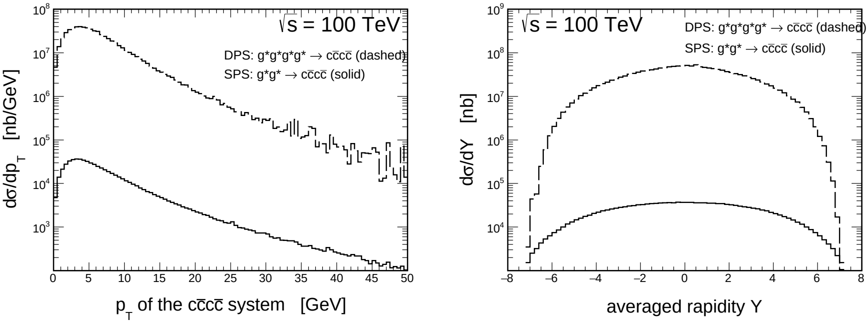
$c\bar{c}c\bar{c}$ production at FCC



Rysunek: Invariant mass distribution of the $c\bar{c}c\bar{c}$ system at $\sqrt{s} =$ 100 TeV.

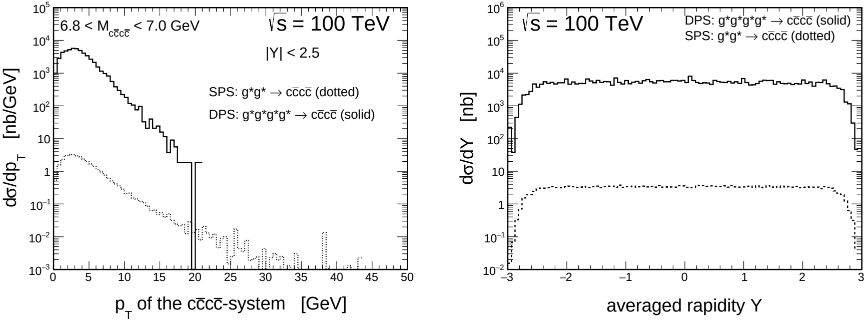
The cross section for DPS $c\bar{c}c\bar{c}$ production is even larger than for SPS $c\bar{c}c\bar{c}$ production compared to $\sqrt{s} = 13$ TeV.

$c\bar{c}c\bar{c}$ production at FCC



Rysunek: Other distributions for the $c\bar{c}c\bar{c}$ system for $\sqrt{s} = 100$ TeV without the tetraquark mass window.

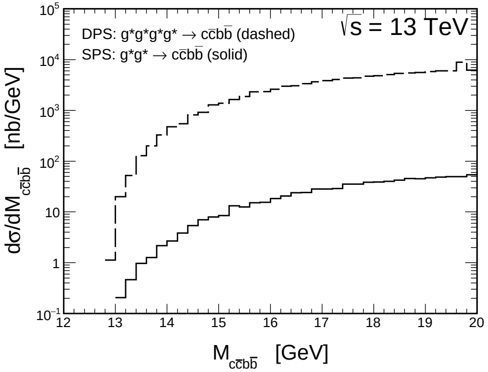
T_{4c} production at FCC



Rysunek: Distributions for the $c\bar{c}c\bar{c}$ system for $\sqrt{s} = 100$ TeV with the tetraquark mass window.

-6.8 GeV $< M_{c\bar{c}c\bar{c}} <$ 7.0 GeV

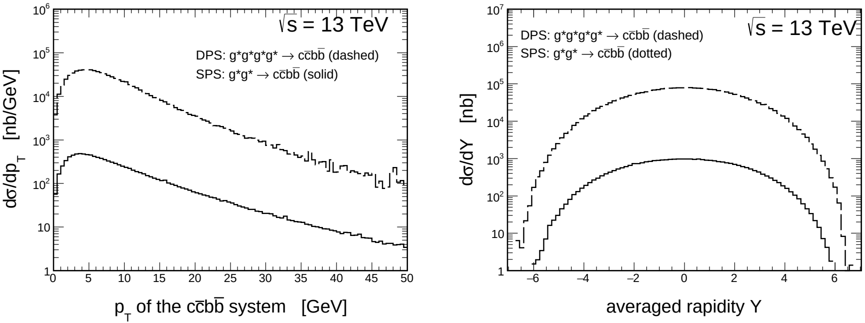
$c\bar{c}b\bar{b}$ production at the LHC



Rysunek: Invariant mass distribution of the $c\bar{c}b\bar{b}$ system.

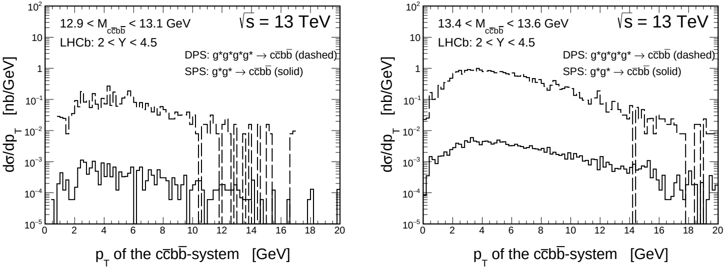
Much smaller cross section than for $c\bar{c}c\bar{c}$ production.
Maximum of the cross section is far from the threshold !

$c\bar{c}b\bar{b}$ production at the LHC



Rysunek: Other distributions for the $c\bar{c}b\bar{b}$ system. No cuts on the tetraquark mass.

Charm-bottom tetraquark - two mass windows



Rysunek: Transverse momentum distribution of the "potential tetraquark"for two invariant mass windows. Here -2.5 $< Y <$ 2.5 was imposed.

We do not know the actual mass of the T_{2c2b} tetraquark
Almost the same result for $(c\bar{c})(b\bar{b})$ and $(cc)(\bar{b}\bar{b})$ or $(\bar{c}\bar{c})(bb)$.

Conclusions

- Possible SPS and DPS mechanisms of T_{4c} production have been discussed.
- The mechanisms of the SPS and DPS $J/\psi J/\psi$ background have been discussed.
- The DPS mechanism of $c\bar{c}c\bar{c}$ production is larger than the SPS mechanism of $c\bar{c}c\bar{c}$ production.
- The results for LHC and FCC have been shown.
- Similar analysis for the T_{2c2b} tetraquark production have been considered for the LHC.
  The cross section seems two orders of magnitude smaller than that for the T_{4c} tetraquark.
- Strong dependence of the cross section on the T_{2c2b} mass window !

Outlook

- Quite probable that at high energies the coalescence mechanism dominates.
- At high energies where $c\bar{c}c\bar{c}$ is abundantly produced such a mechanism seems very probable.
- Our coalescence mechanism leads to very small cross section close to $c\bar{c}c\bar{c}$ $(J/\psi J/\psi)$ threshold.
  It can mean that the cross section for production of $g.s.$ tetraquark may be very small.
- In addition, the branching ratio into charged leptons may be small.
- $D\bar{D}$ may be difficult channel –
  multihadron state and huge background.
  Compare the $D\bar{D}$ background to $J/\psi J/\psi$ background.
- Try to measure $J/\psi\Upsilon$. So far such a channel was not measured.
- Calculation with $gg \to T(c\bar{c}c\bar{c})$ with realistic tetraquark wave function is needed. This is rather difficult.